Direct detection of exoplanets with ground-based telescopes

Bruce Macintosh

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Gemini Planet Imager

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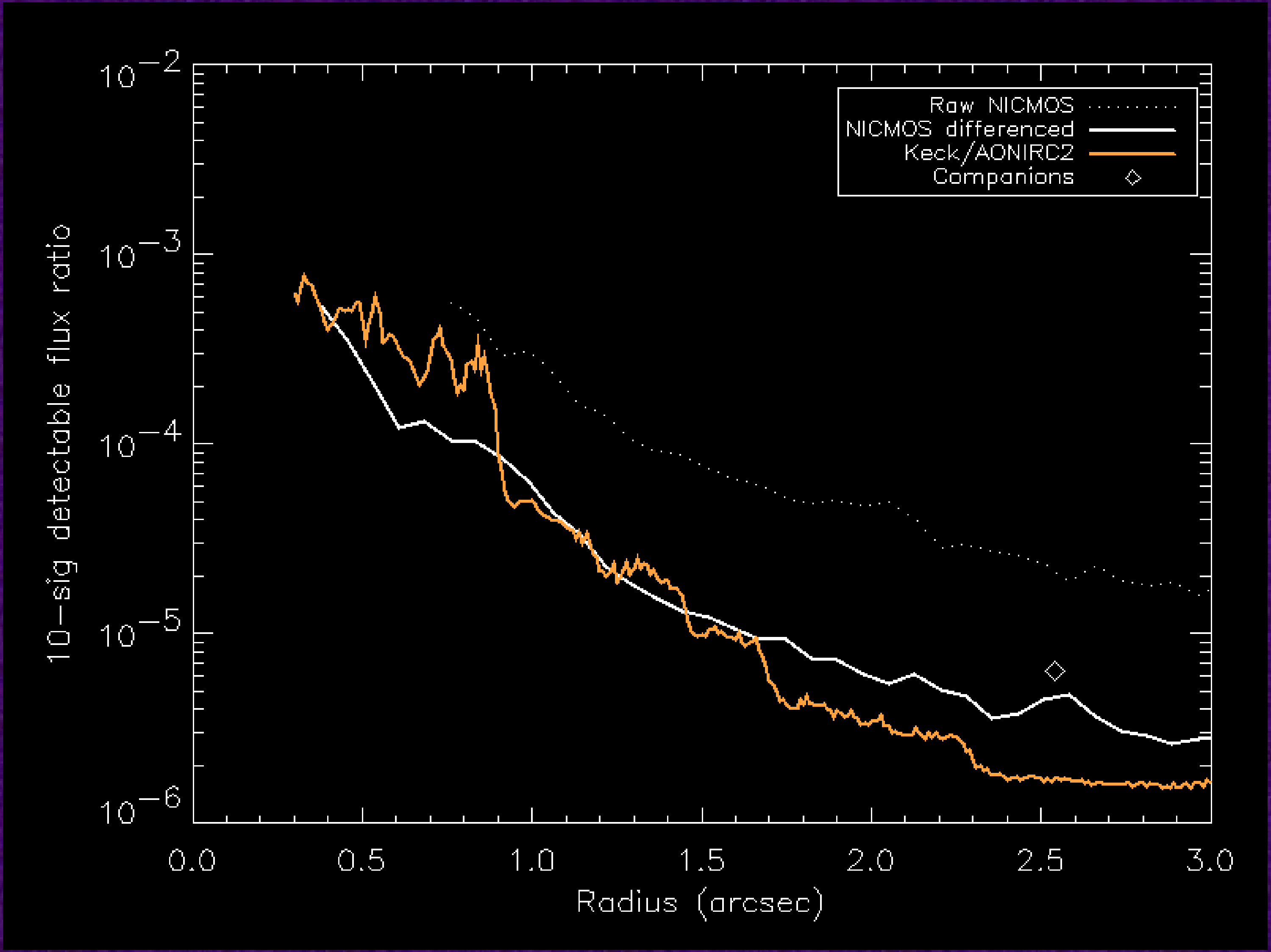
Outline

- A brief mention of interferometers
- Current AO sensitivity
- Future “Extreme AO” sensitivity
- Representative 8-m ExAO: Gemini Planet Imager
- Further-future Extremely Large Telescopes

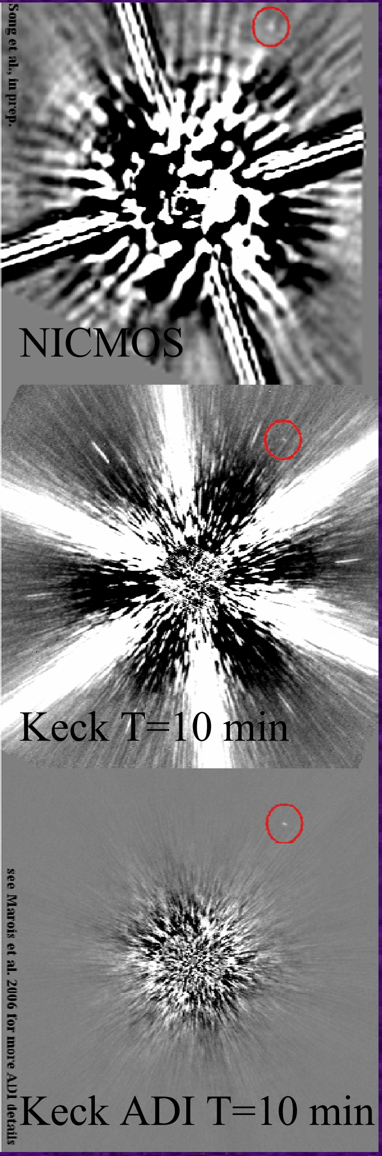
Interferometry

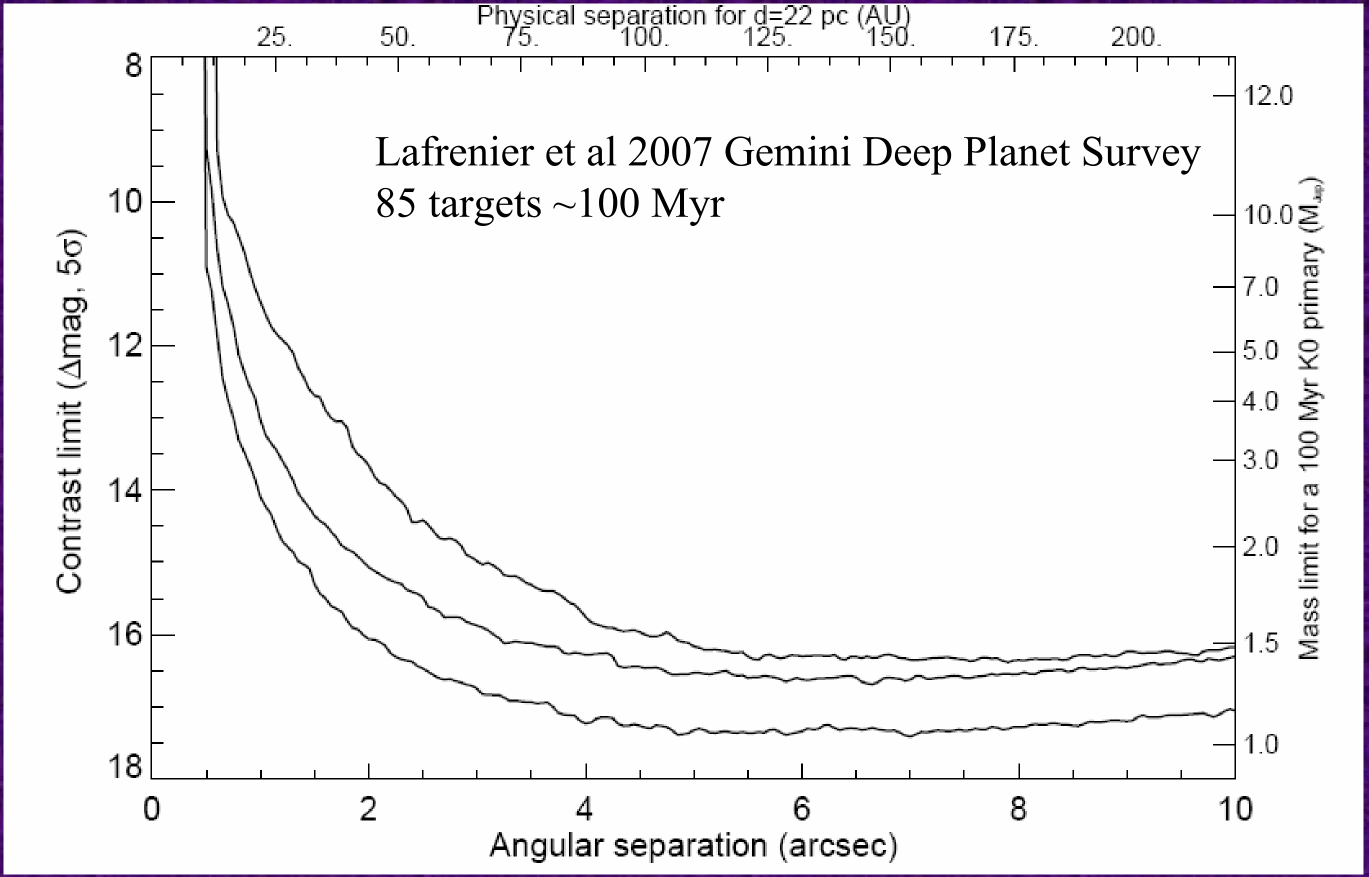
- **Most scientific results from Keck and VLT interferometers are young star disks**
- **Keck + LBT interferometer nullers designed for observations of Zodiacal disks (>10-100xSolar)**
- **No significant direct planet detection capability**
- **Astrometric upgrades to 50uas give some planet-characterizing capability**
  - Require bright reference source nearby (except for South Pole…)
  - 3 known multi-planet systems, 25-35 single-planet systems
  - New Saturn analogs?

Keck and NICMOS ~2000



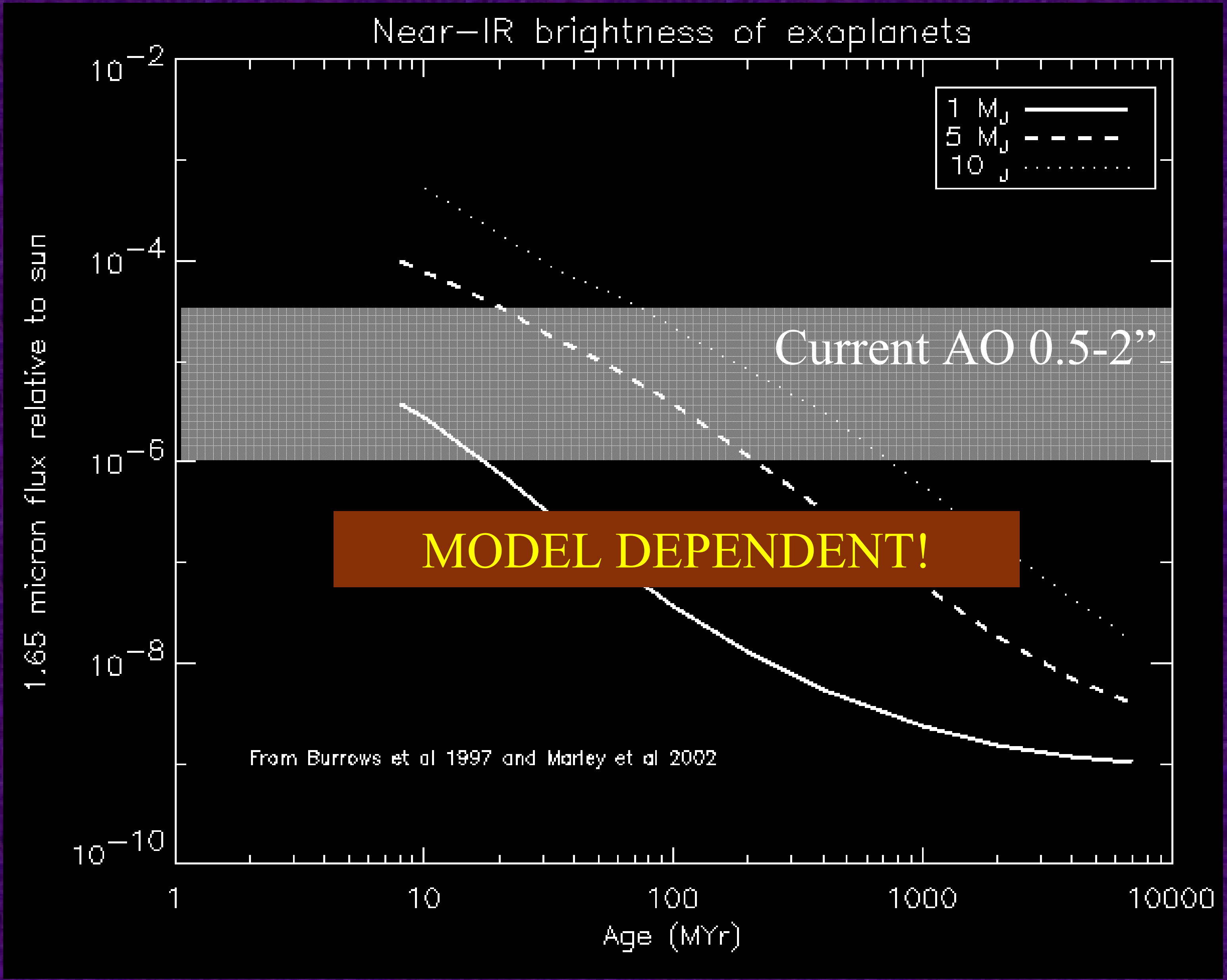
Current state of the art





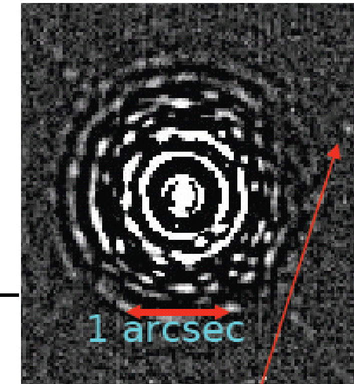
- **Siderial-rotaton (Marois et al 2006), multiwavelength imaging (Hiller et al 2007), systematic long-exposure surveys**
  - Still limited at <0.5”
- **HST (w. ACS) superior for quantitative studies of debris disks**

Cooling extrasolar planets ("hot start")

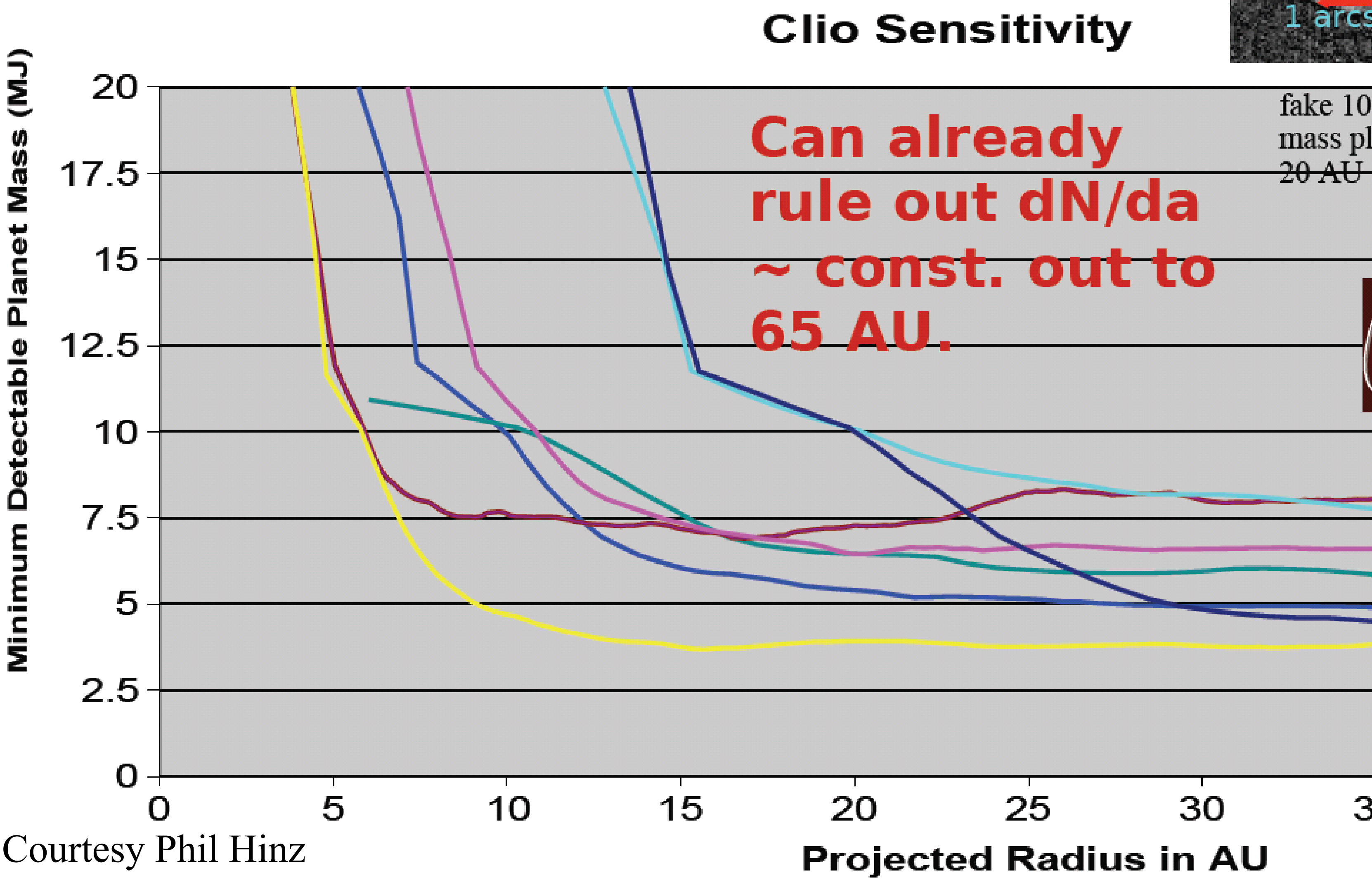


MMT L' band Planet Survey Underway

- Heinze et al. have observed ~40 stars to date

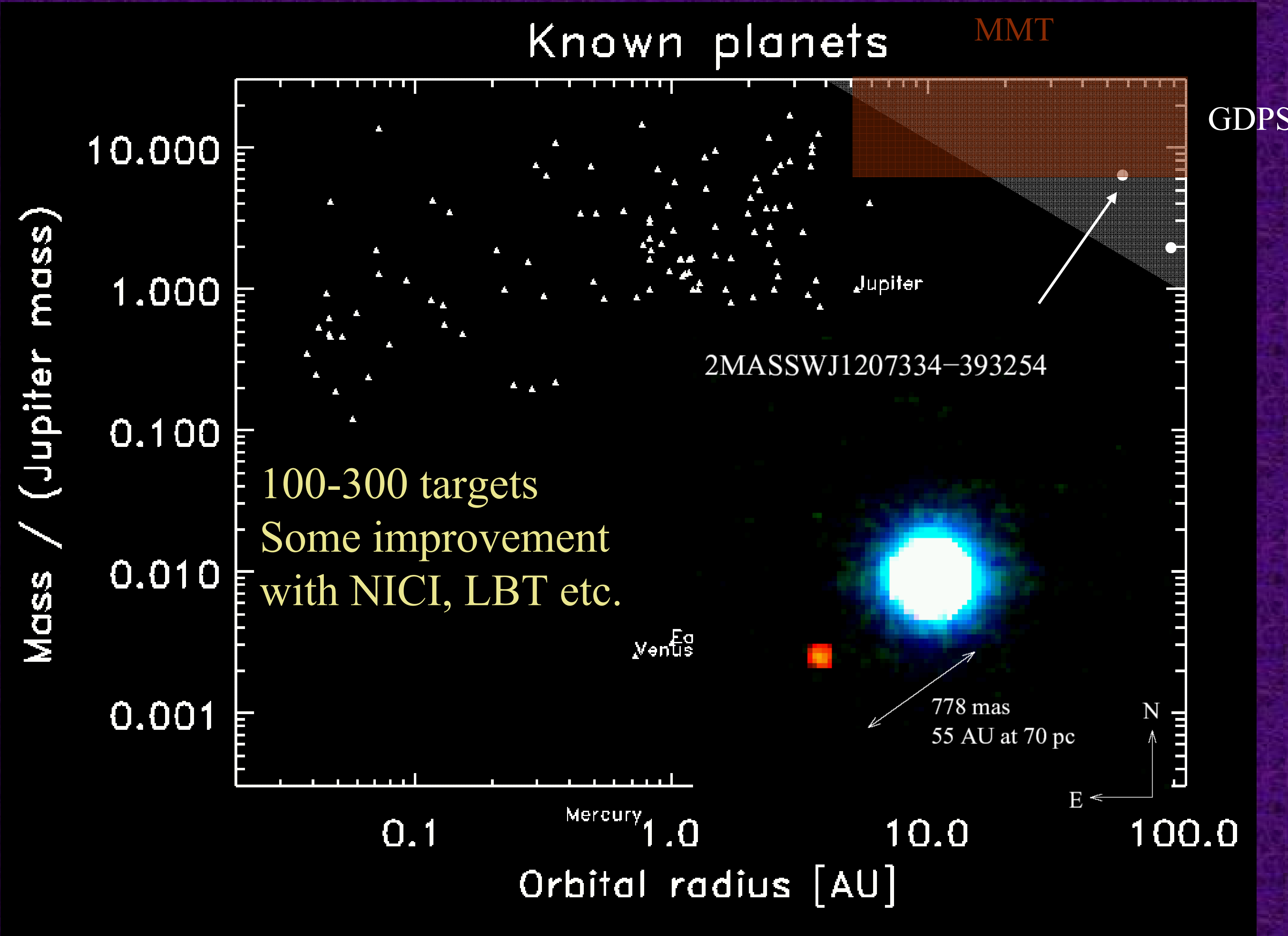


fake 10 Jupiter mass planet at 20 AU

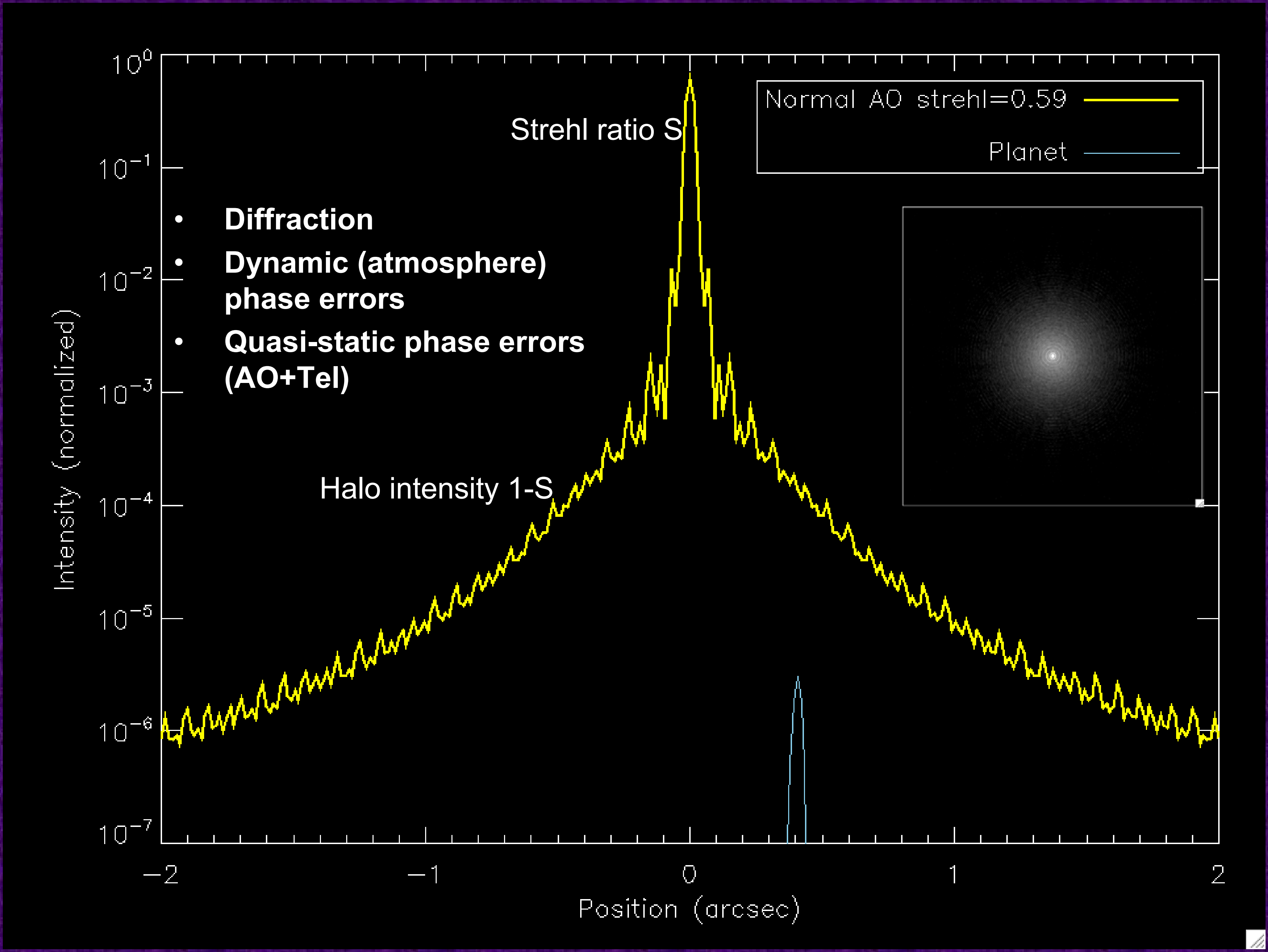


Can already rule out dN/da ~ const. out to 65 AU.

Courtesy Phil Hinz



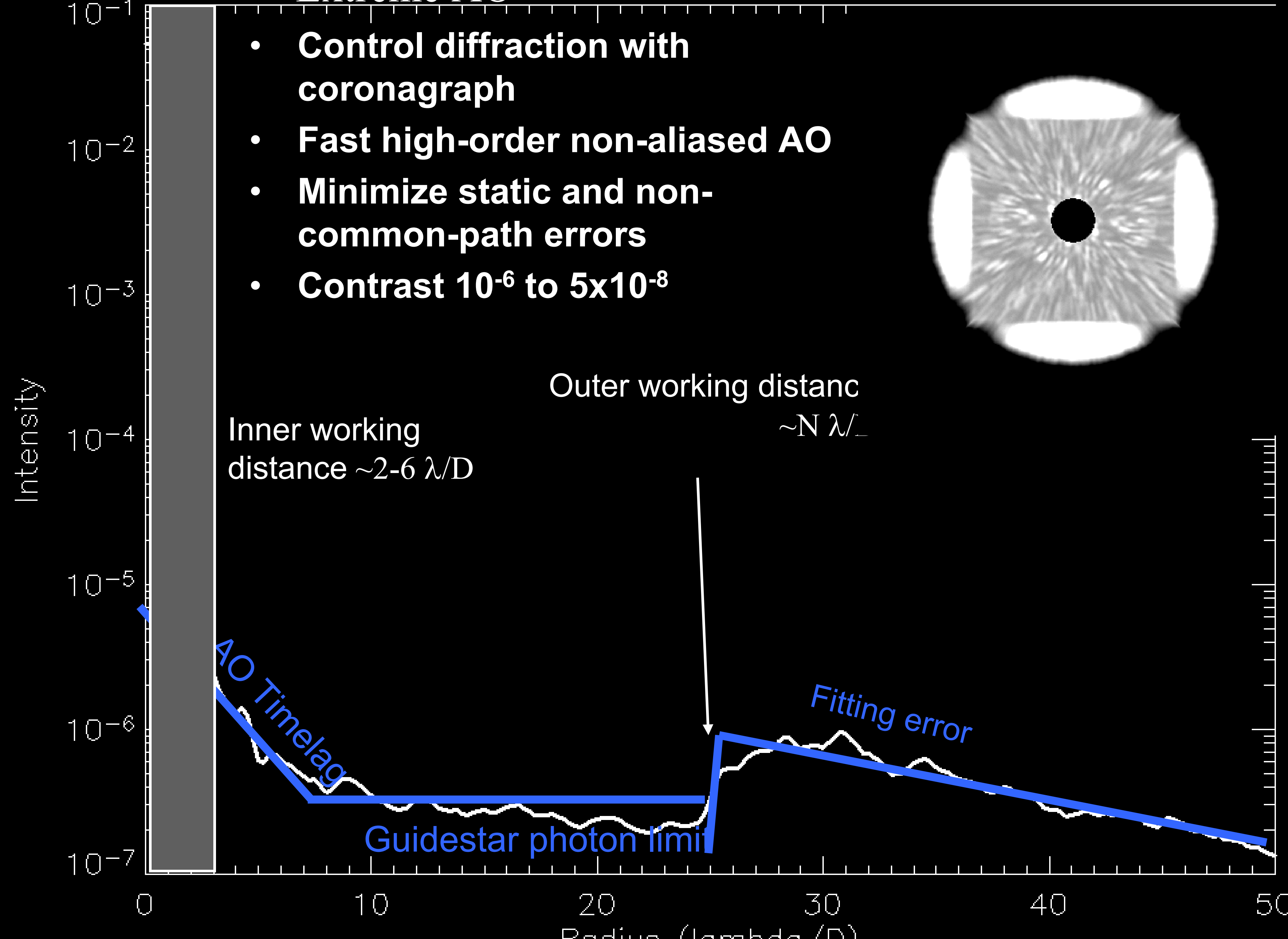
Known planets
MMT
GDPS
Mass / (Jupiter mass)
10.000
1.000
0.100
0.010
0.001
Jupiter
2MASSWJ1207334−393254
100-300 targets
Some improvement
with NICI, LBT etc.
Ea
Venus
778 mas
55 AU at 70 pc
N
E
Mercury
0.1
1.0
10.0
100.0
Orbital radius [AU]



Strehl ratio S
Normal AO strehl=0.59
Planet
• Diffraction
• Dynamic (atmosphere) phase errors
• Quasi-static phase errors (AO+Tel)
Halo intensity 1-S
Intensity (normalized)
Position (arcsec)
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
−2
−1
0
1
2

Extreme AO

- **Control diffraction with coronagraph**
- **Fast high-order non-aliased AO**
- **Minimize static and non-common-path errors**
- **Contrast 10^{-6} to 5×10^{-8}**



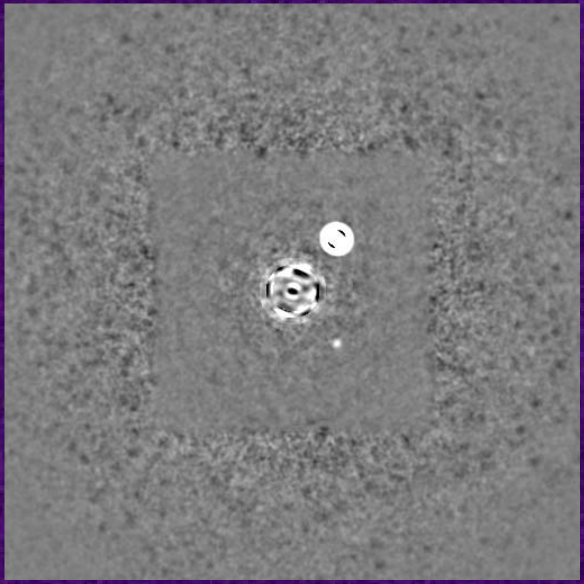
Gemini Planet Imager

Gemini-funded facility ExAO system + coronagraph + spectrograph

2006: (June): Project start

2010: (December): First light on Gemini South

Science design emphasizes target reach (~1000 high-priority targets) for statistically robust samples



Team

LLNL: Project lead + AO

AMNH: Coronagraph masks&design

HIA: Optomechanical + software

JPL: IR Interferometer WFS

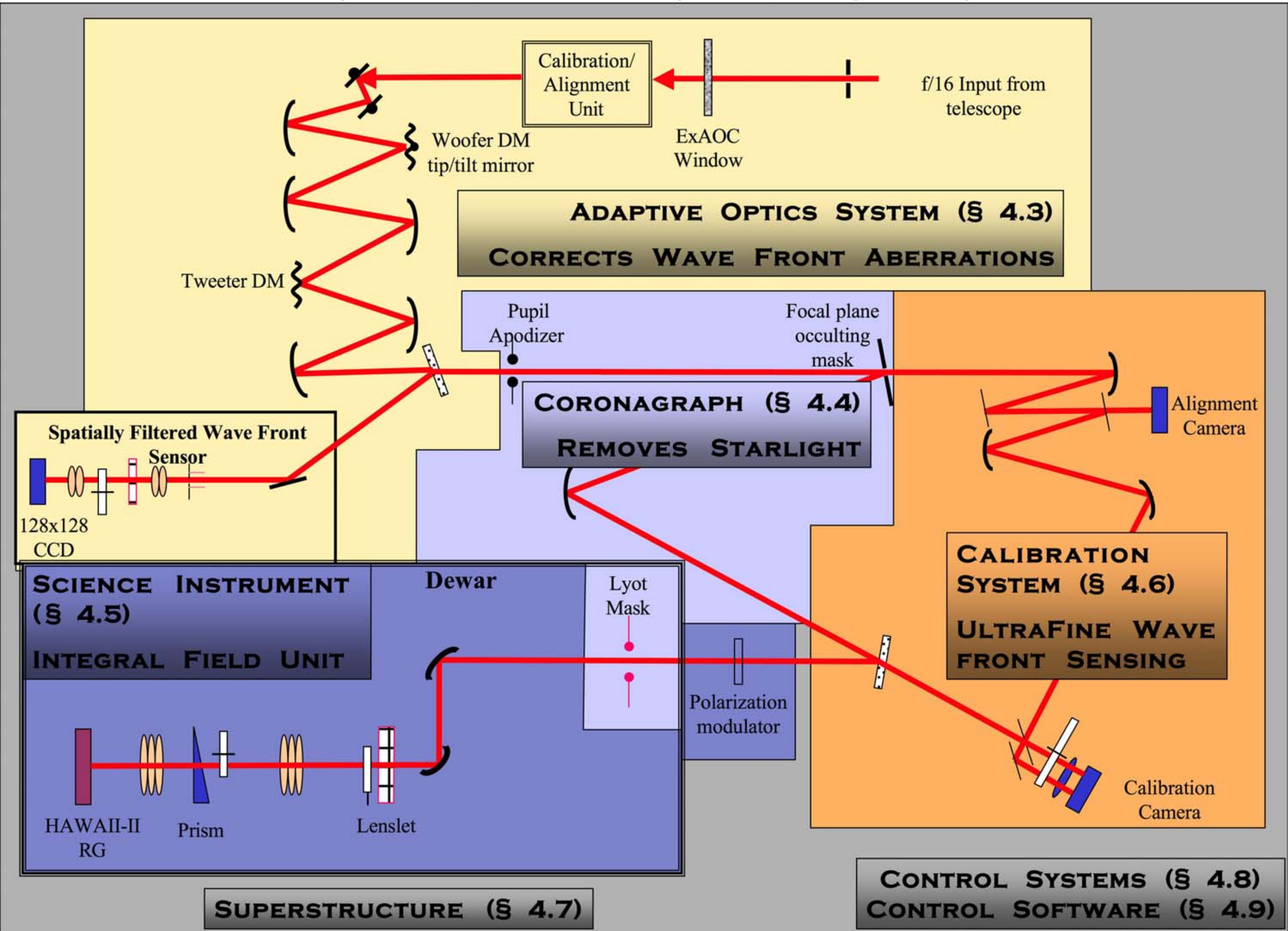
UCB: Science modeling

UCLA: IR spectrograph

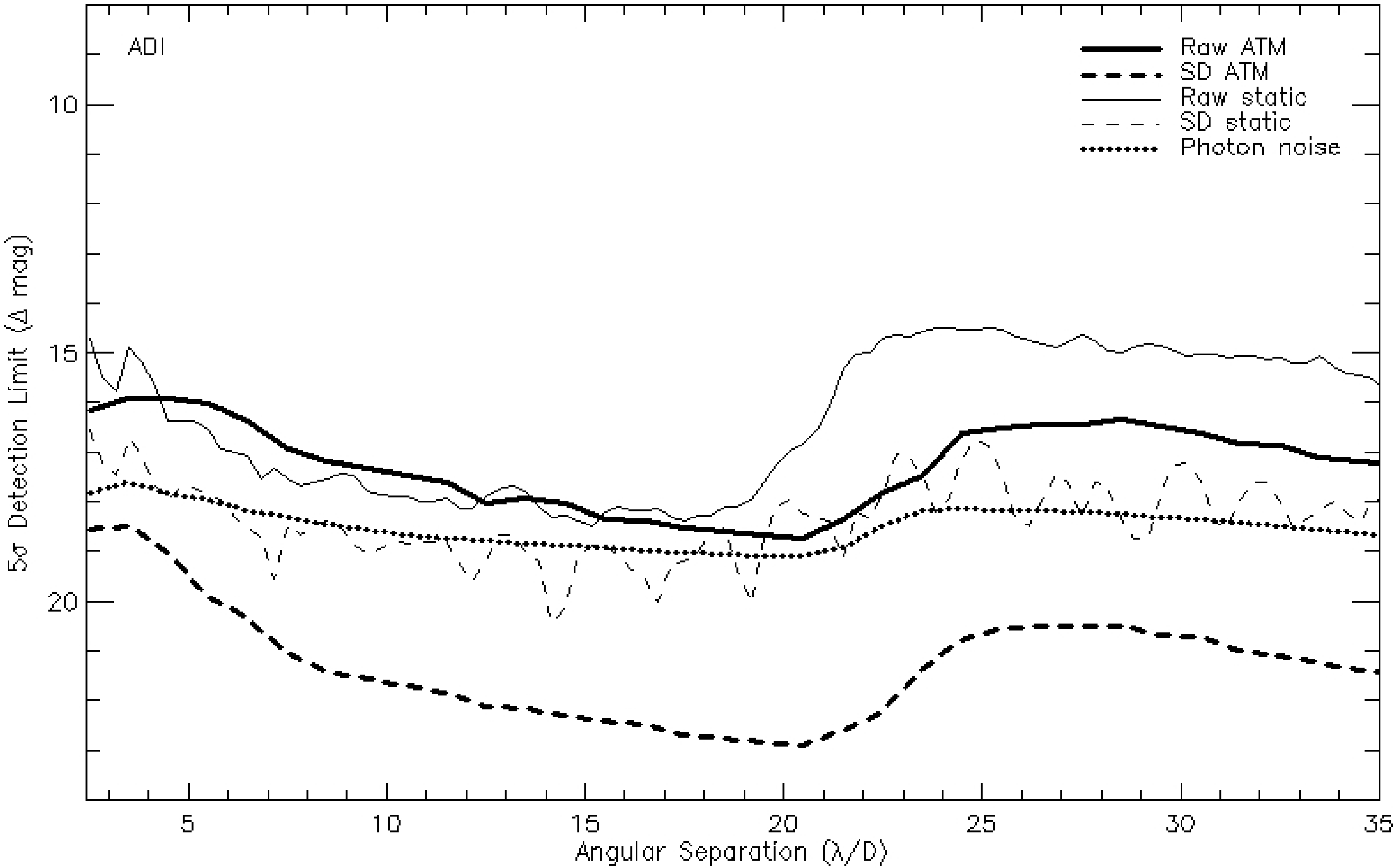
UdM: Data pipeline

UCSC: Final integration&test

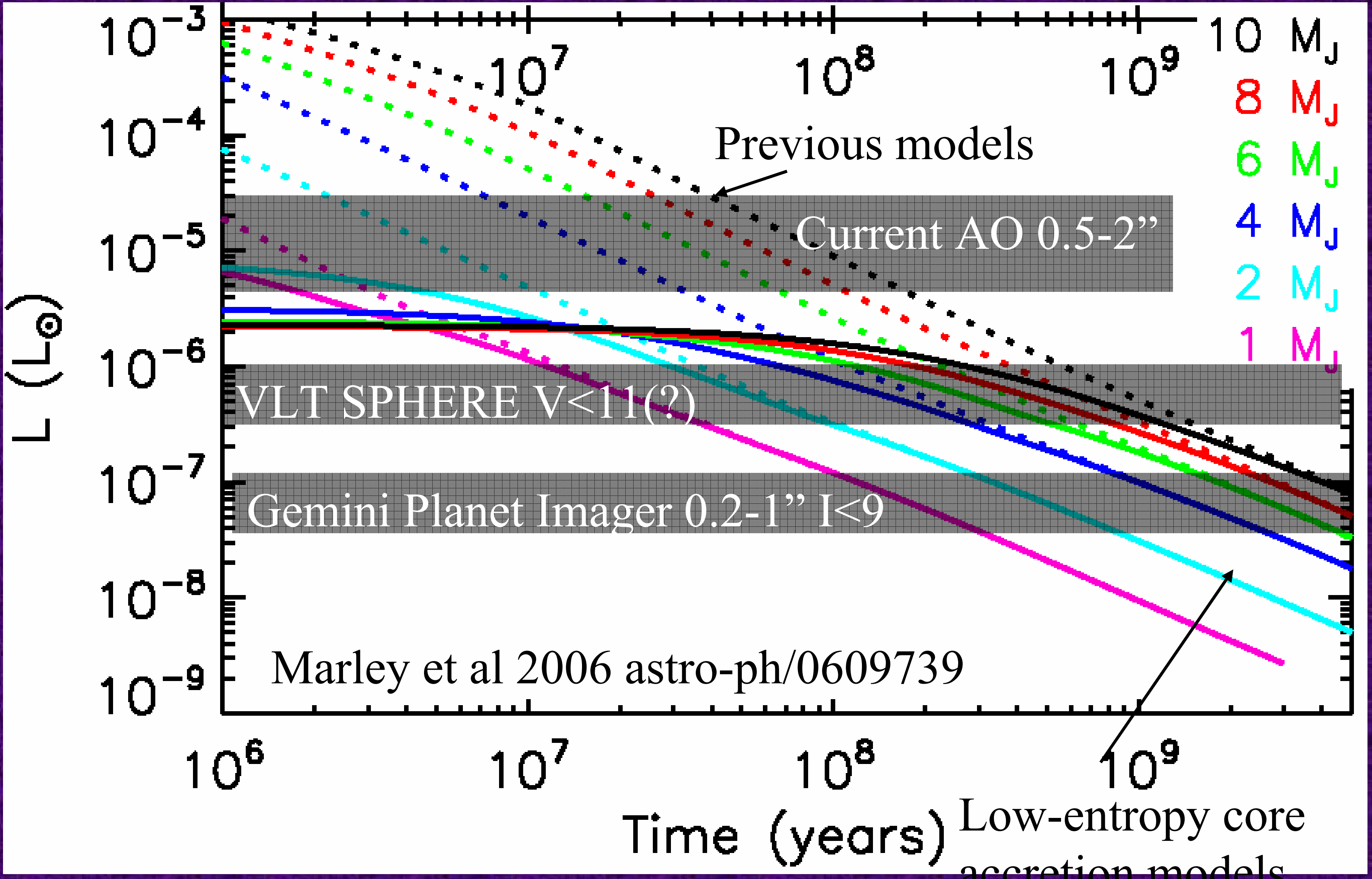
ExAOC System Overview

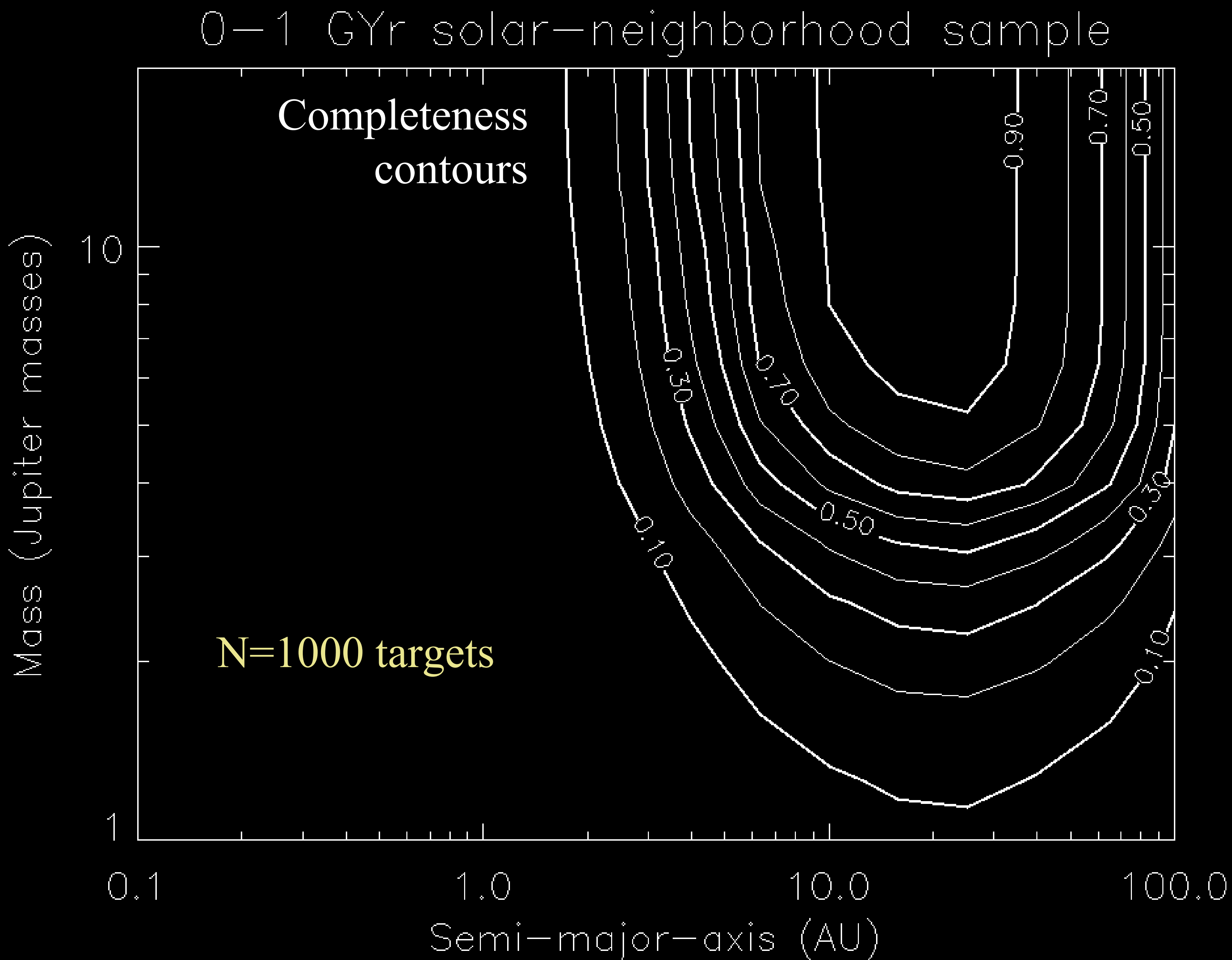


GPI performance *I*=6 r0=14 cm 2 hr
From dynamic AO + static Fresnel sims

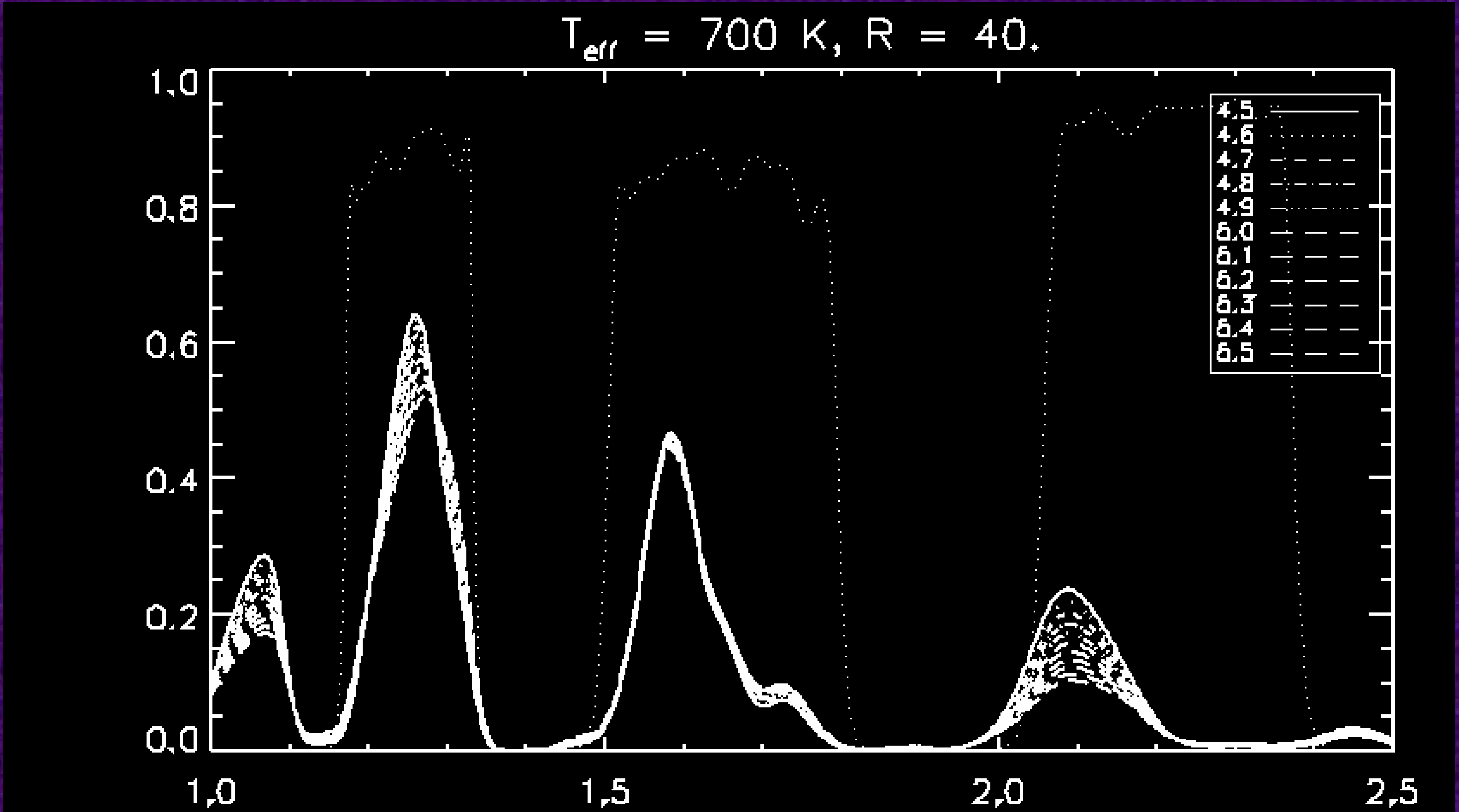


Contrast and model dependence




0−1 GYr solar−neighborhood sample
Completeness contours
N=1000 targets
0.90
0.70
0.50
0.30
0.10
10
1
0.1
1.0
10.0
100.0
Mass (Jupiter masses)
Semi−major−axis (AU)

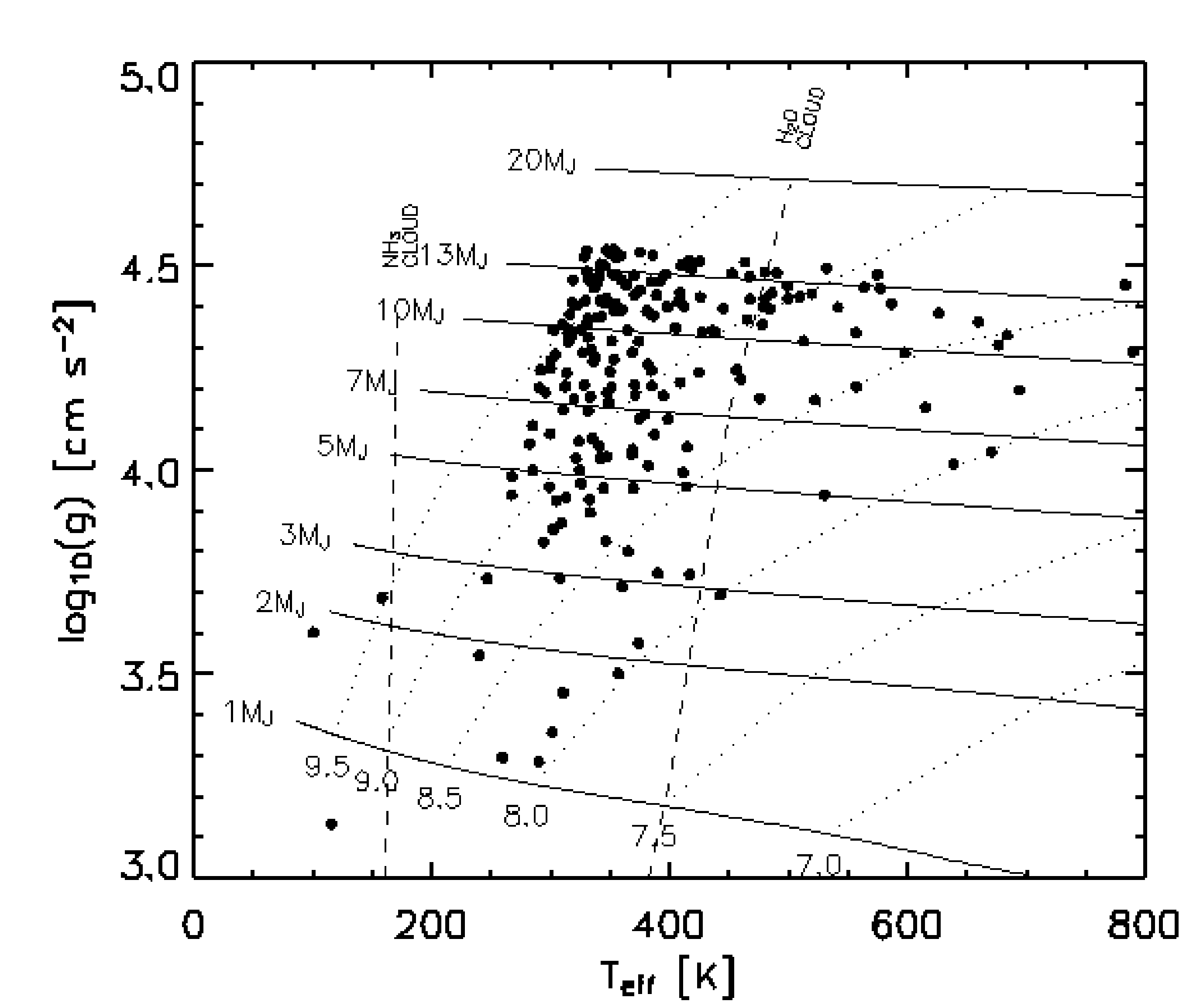
Spectral characterization



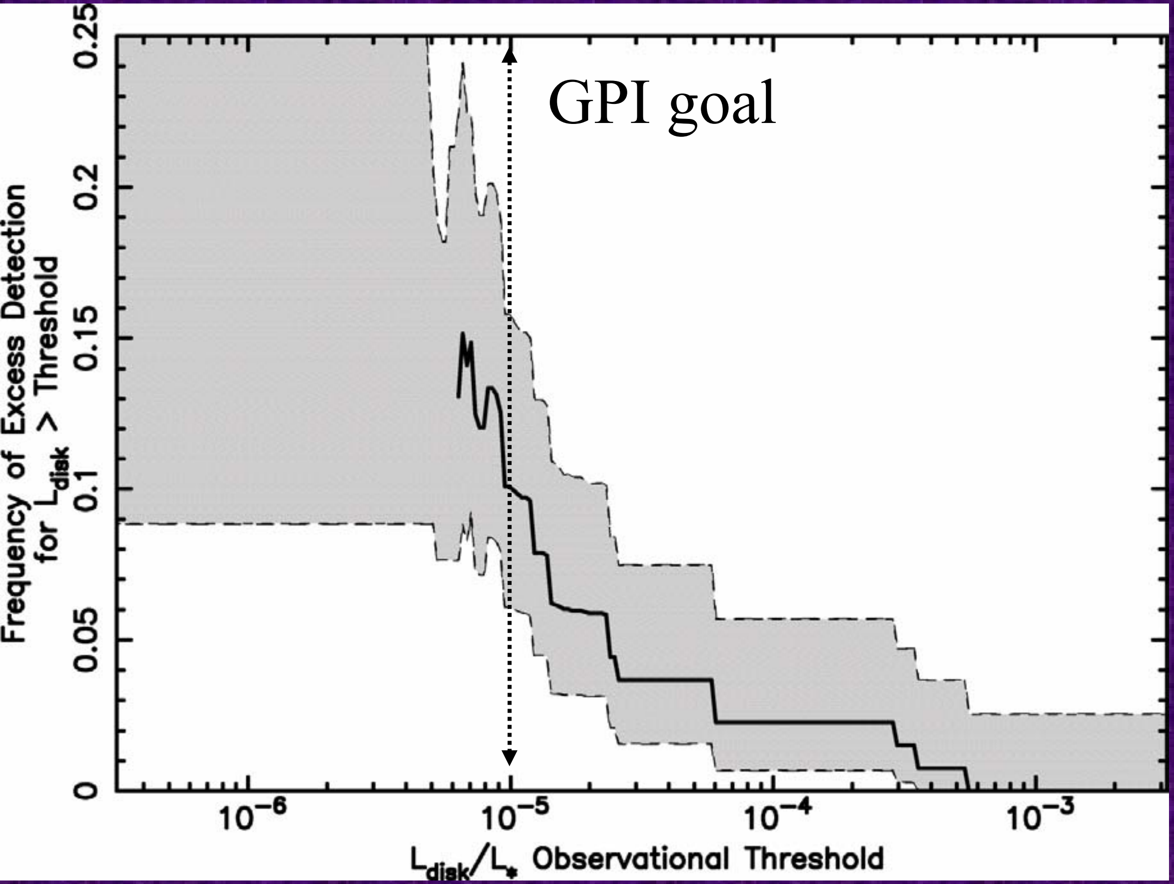
Brown dwarf spectra from UofA group

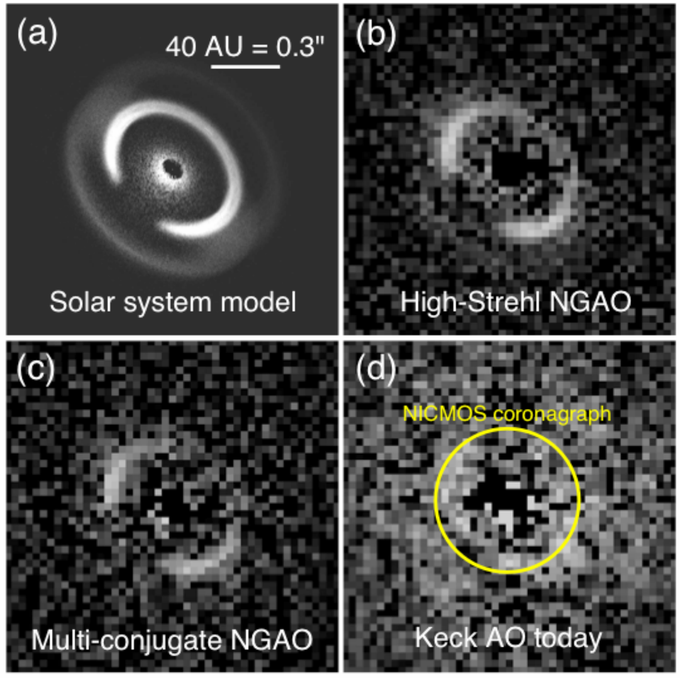
- SNR=5-10 H-band spectra of all detection; SNR=10-20+ 1-2.5 YJHK followup
- Measure Teff, L + estimate star age
- log(g) measurements constrain mass/composition/models
  - **Astrometry is very complementary**

GPI Field Star Survey



Debris Disks trace solar systems



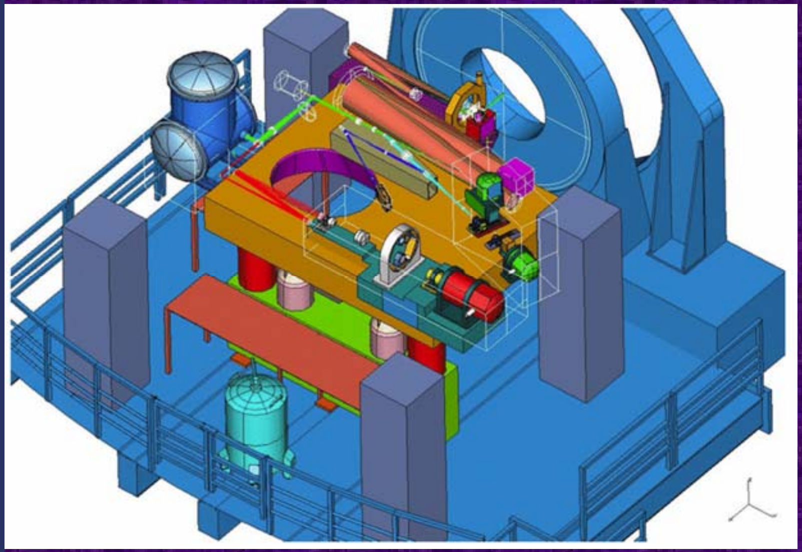


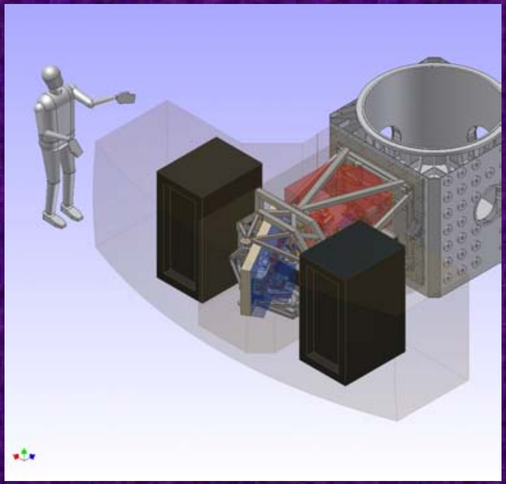
100 Myr solar system model (Metchev, Wolf) with $\tau \sim 10^{-3.5}$ at 130 pc from Keck NGAO study

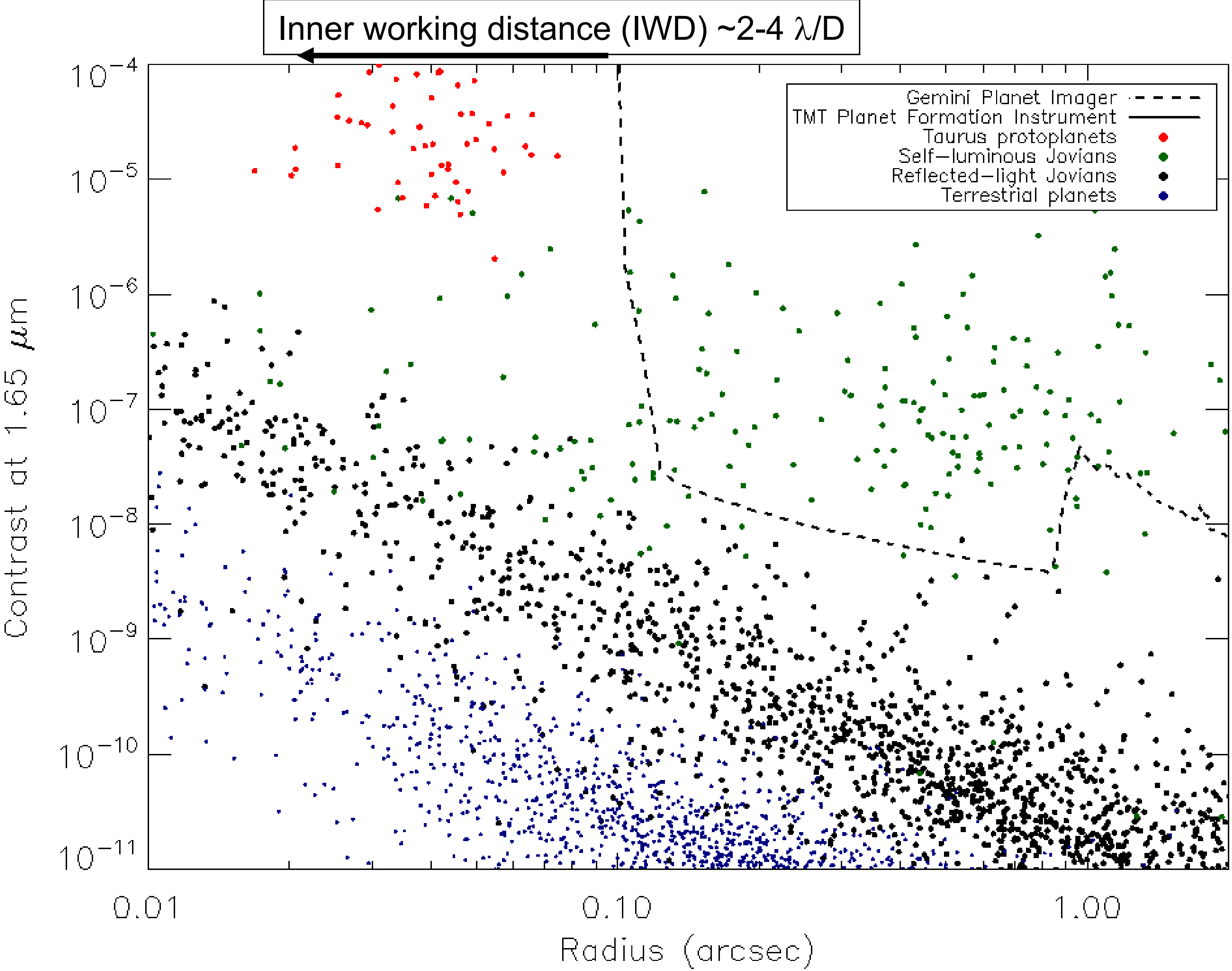
- **Dual-channel polarimetry, self-calibrating PSF for detection of faint debris disks**
- **AU Mic/50 detectable at near-face-on inclination**

ExAO on Gemini and VLT: Summary

- **GPI and VLT SPHERE first light late 2010**
- **Similar capabilities**
  - SPHERE emphasizes fainter (younger) stars at lower contrast
  - SPHERE has visible-light polarimeter
  - GPI has higher IFS resolution, better K-band
  - Subaru HiCIAO upgrade: intermediate
- **Observatories are committed to 100-night+ large-scale surveys**
- **Surveys will provide planet statistics in 5-50 AU range**
- **Spectral characterization of a large sample of self-luminous planets**

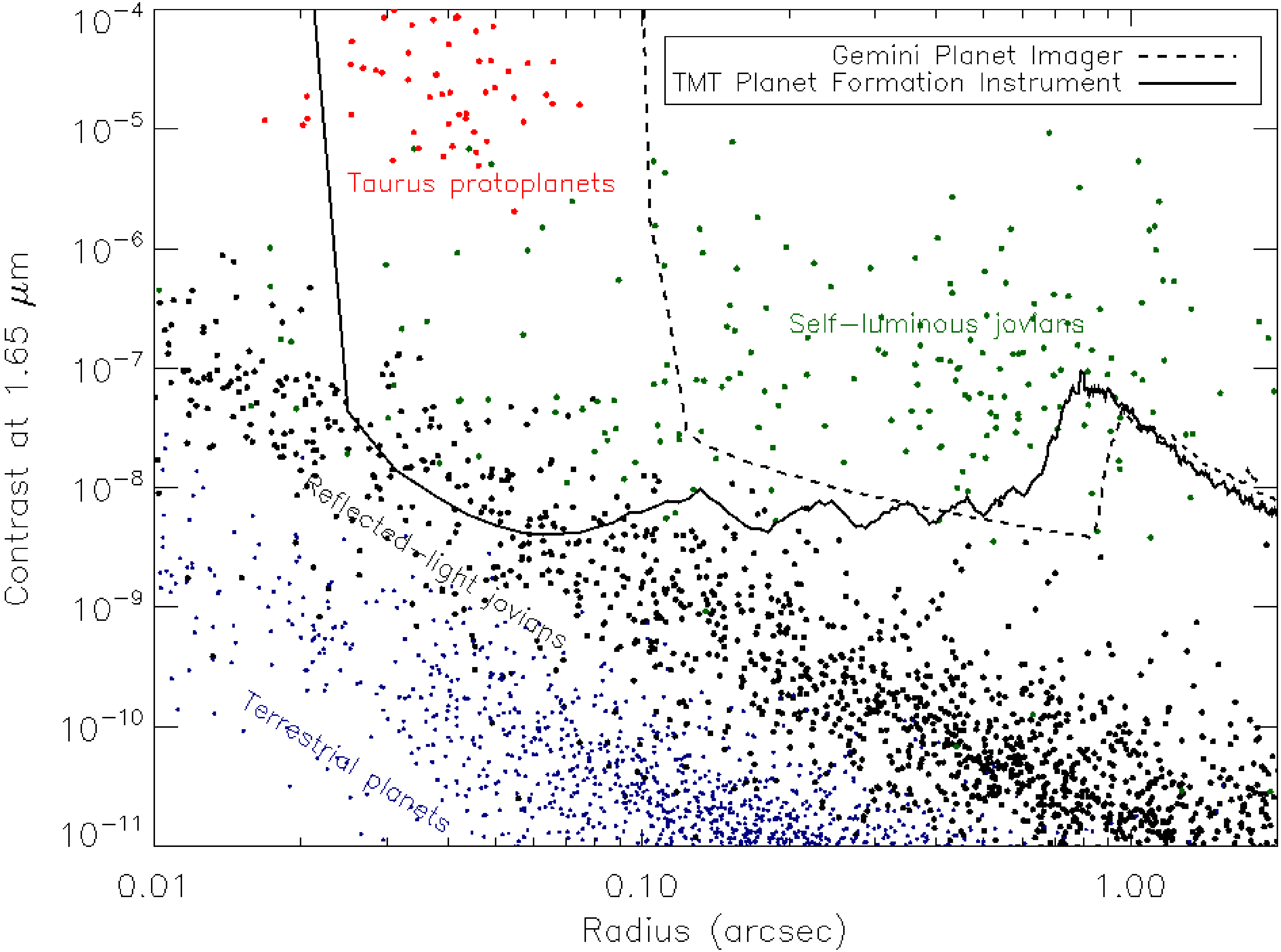




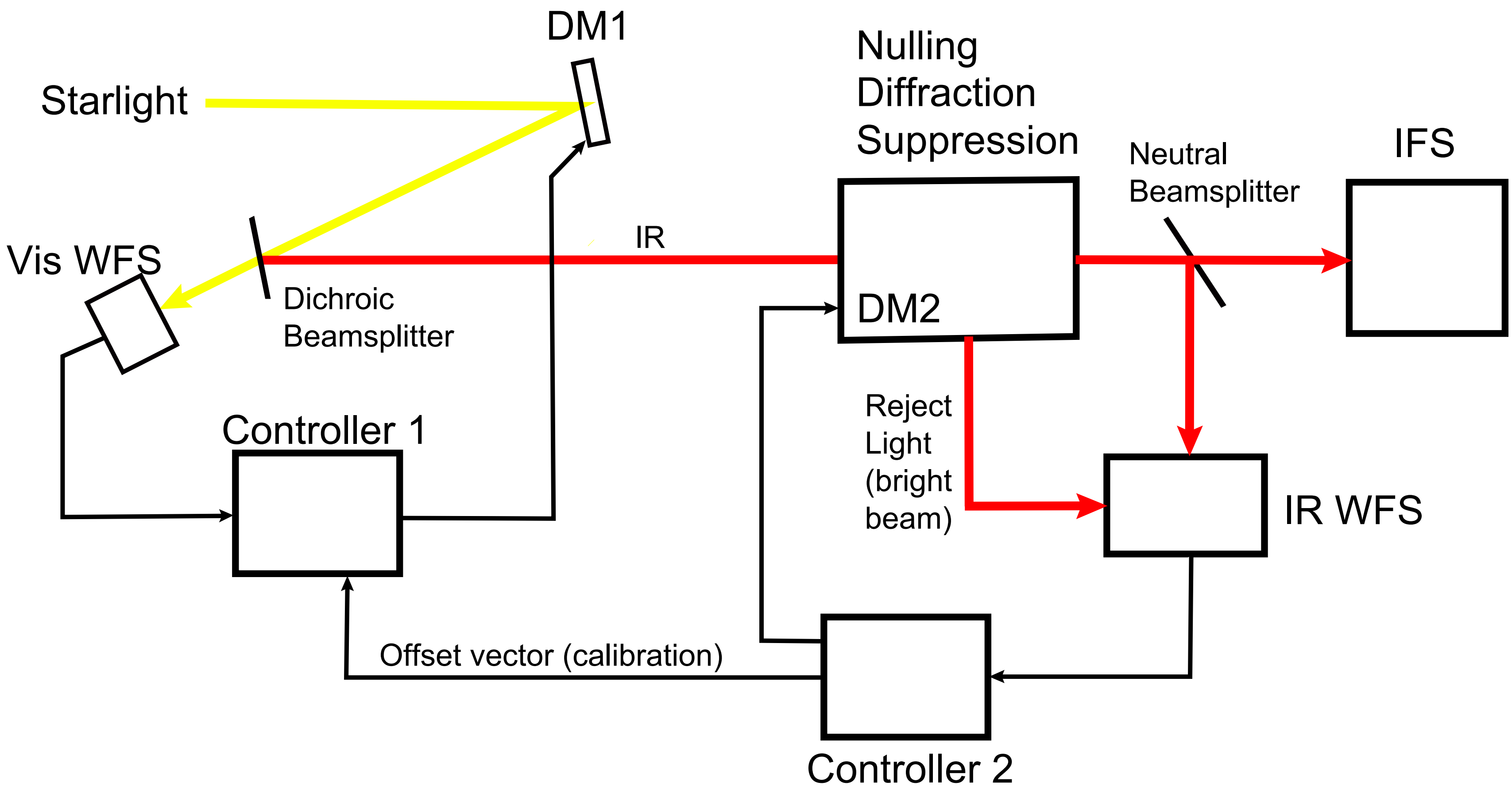


Inner working distance (IWD) ~2-4 λ/D
Gemini Planet Imager
TMT Planet Formation Instrument
Taurus protoplanets
Self−luminous Jovians
Reflected−light Jovians
Terrestrial planets
10^−4
10^−5
10^−6
10^−7
10^−8
10^−9
10^−10
10^−11
Contrast at 1.65 μm
0.01
0.10
1.00
Radius (arcsec)

TMT Planet Formation Imager



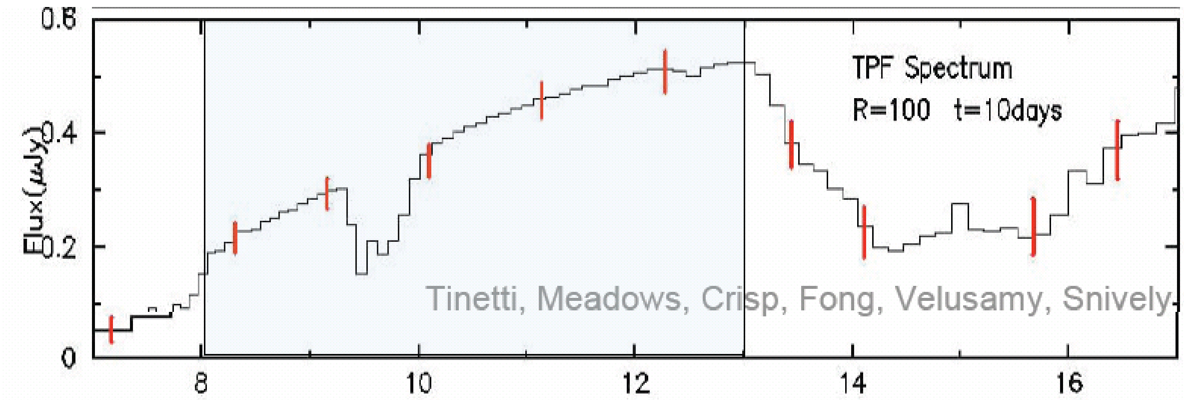
Example: TMT Planet Formation Imager



IR WFS (H<11 mag), small IWD (0.03 arcsec)

GSMT thermal detection of rocky planets

Courtesy Phil Hinz



The Stellar Sample for a detection at 4 microns

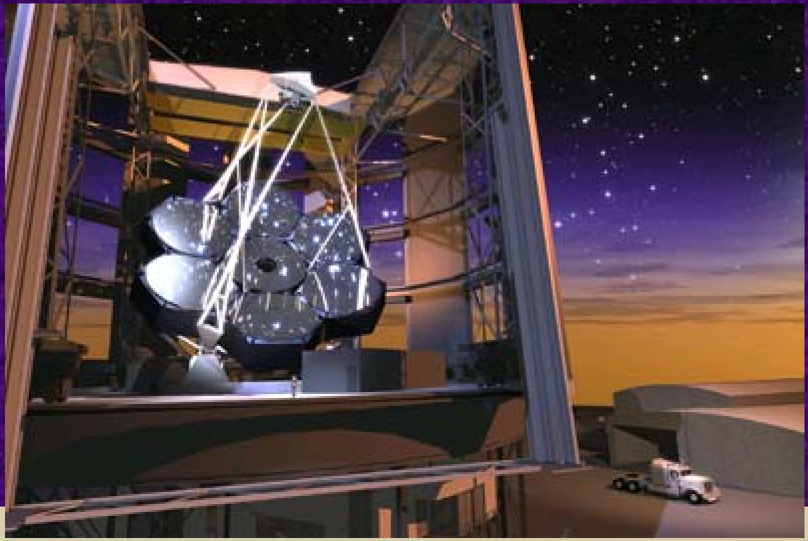
Star	d (pc)	a=600 K (AU)	ang. dist. (")	hot Earth (uJy)	mini. size (R_e)
Alpha Cen A	1.35	0.23	0.17	109.74	0.14
alpha Cen B	1.35	0.14	0.1	109.74	0.14
Sirius	2.64	1.37	0.52	28.7	0.26
eps Eri	3.22	0.12	0.04	19.29	0.32
Procyon	3.5	0.38	0.11	16.33	0.35
tau Ceti	3.65	0.17	0.05	15.01	0.37
Altair	5.14	0.73	0.14	7.57	0.51
beta Hyi	7.47	0.46	0.06	3.58	0.75
Fomalhaut	7.69	1.07	0.14	3.38	0.77
beta Leo	11.1	1.07	0.1	1.62	1.11

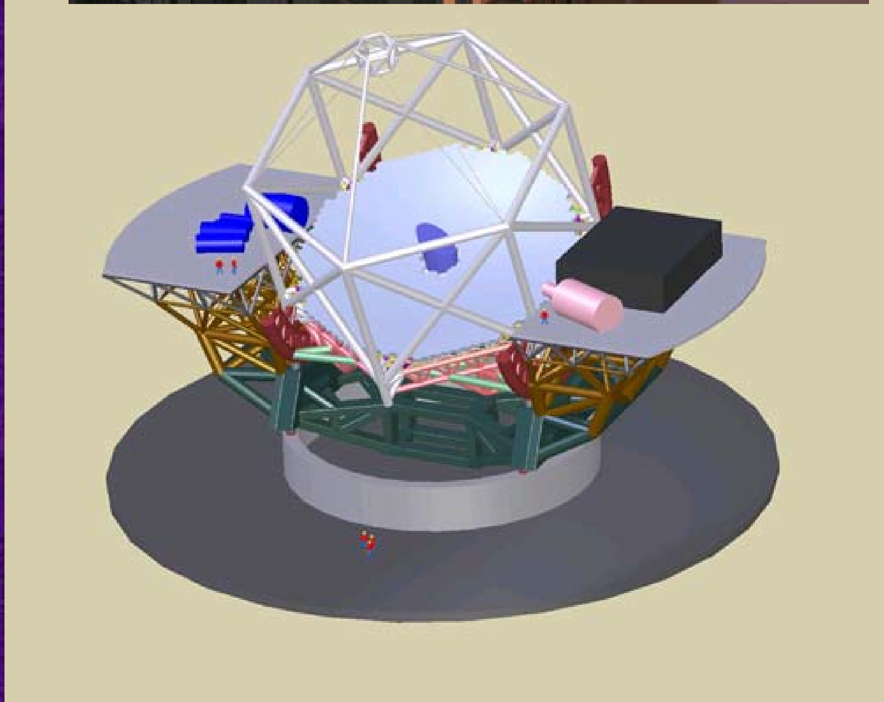
Blue = systems with planet separation less than 3 l/D = 0.1"

Brightness limit=2 uJy

Extremely Large Telescopes: Summary

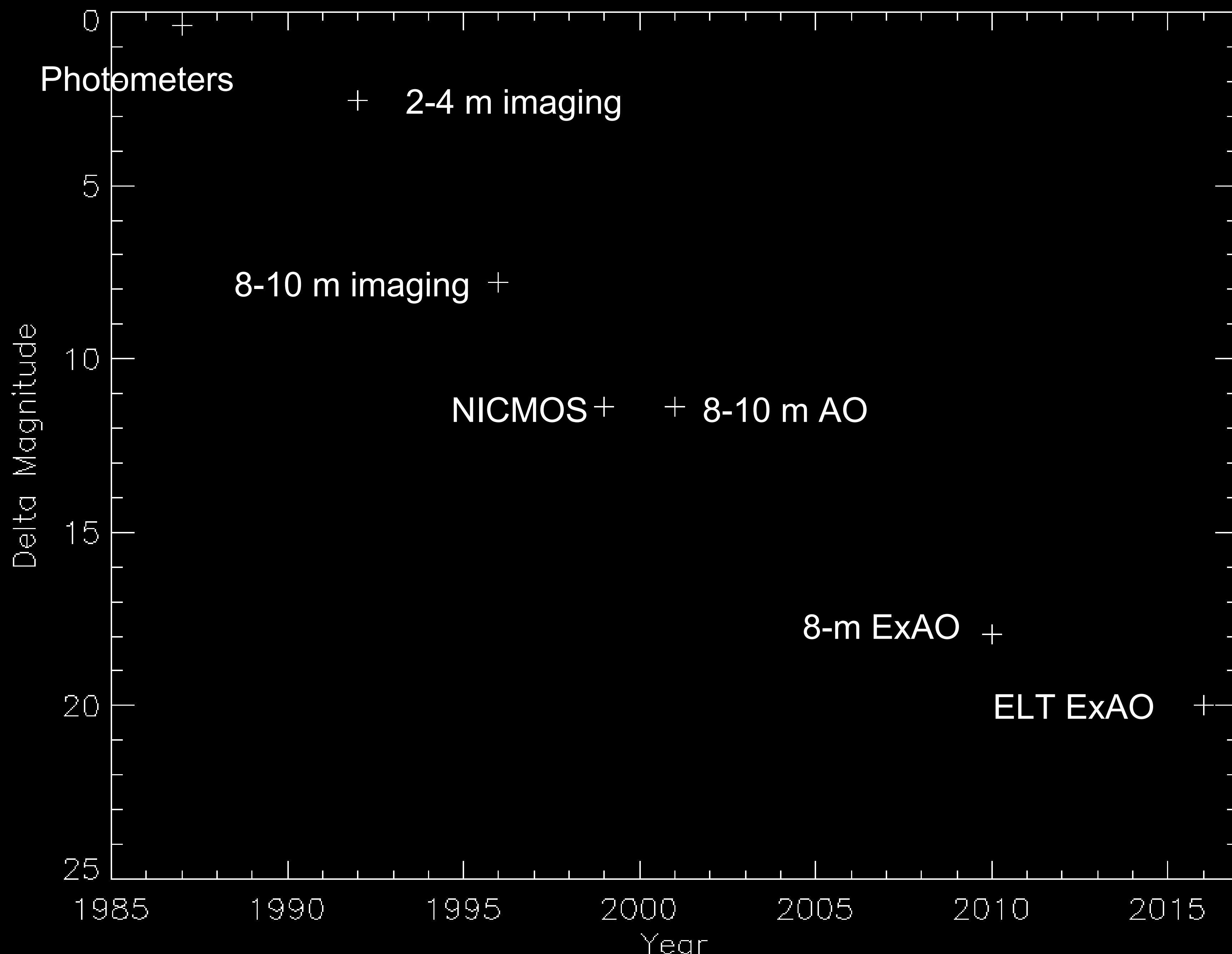
- **Both US designs have broadly similar capabilities**
  - Advantages and disadvantages to both approaches for some aspects of science case
  - European ELT slightly larger; better capability for very close planets
- **Direct detection science:**
  - Reflected-light giant planets at 1-2 AU (down to Saturn?)
  - Thermal IR giant planets
  - NIR young planets 1-50 AU
  - High-res spectroscopy for composition
  - Planet formation at 4-5 AU in Taurus / Ophiucus
  - A few thermal IR rocky planets?
- **Planet detection capability not necessarily the highest priority**
  - ELT first-light suites may be 2 instruments





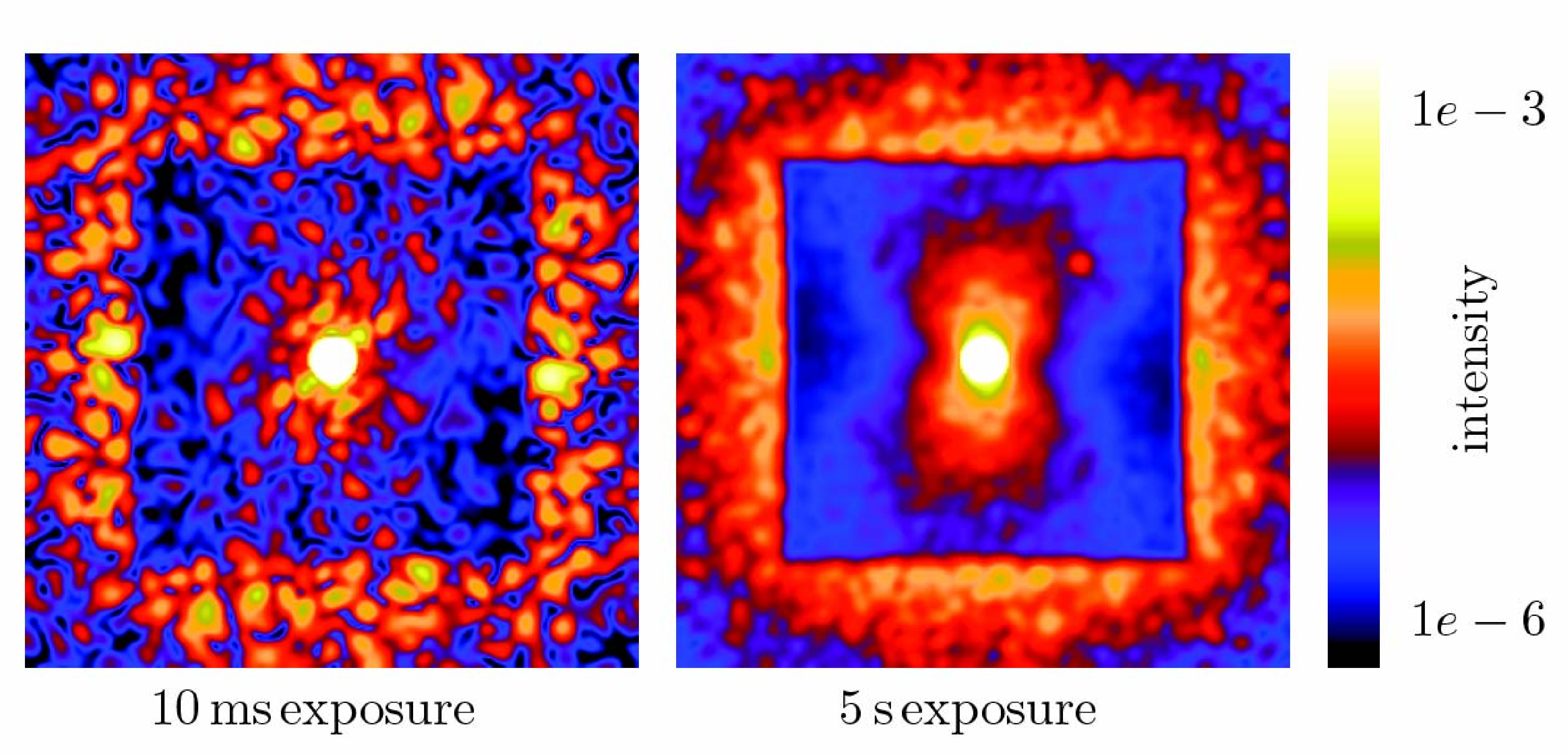
Direct detection conclusions

- **Considerable technological complementarity with space coronagraphs**
- **Direct detection surveys can probe planet phase space inaccessible to other techniques**
  - 5-50 AU for GPI/Sphere
- **Produce moderate-resolution spectra of a large sample of giant planets**
  - Self-luminous planets for GPI/Sphere
  - Reflected-light 1-2 AU planets for ELT
- **Debris disk and other science**
- **Two facility-level 8-m ExAO systems in design**
  - Enabling technologies in place
  - Supported by end-to-end modeling, systems engineering
  - Observatories committed to 100s of nights and 1000s of targets
- **ELT ExAO will have unique capabilities**
  - Reflected-light giant planets at 1-2 AU
  - 4-5 AU in Taurus / Ophiucus



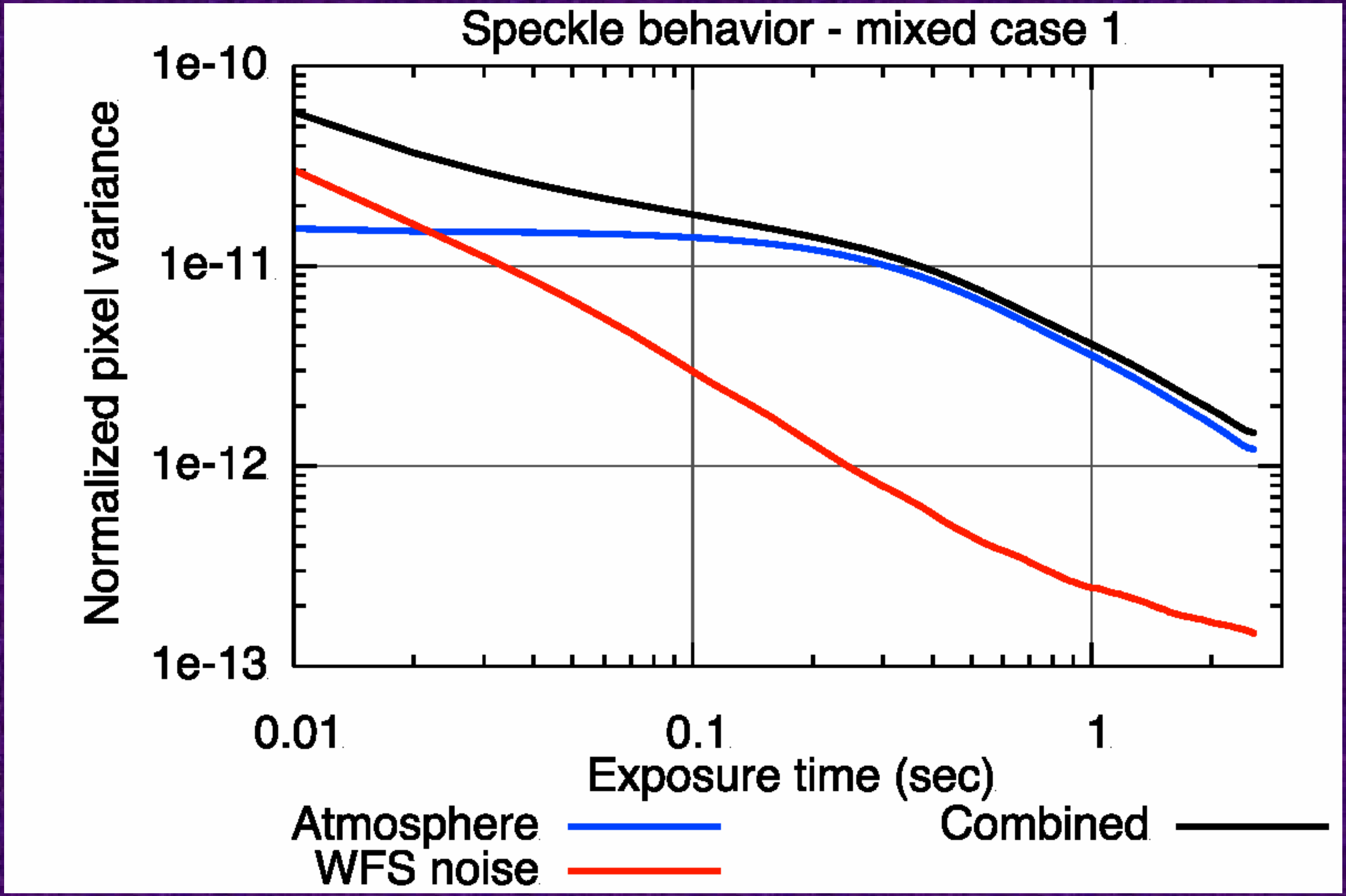
Photometers
2-4 m imaging
8-10 m imaging
NICMOS
8-10 m AO
8-m ExAO
ELT ExAO
Delta Magnitude
Year
0
5
10
15
20
25
1985
1990
1995
2000
2005
2010
2015

PSF speckle evolution



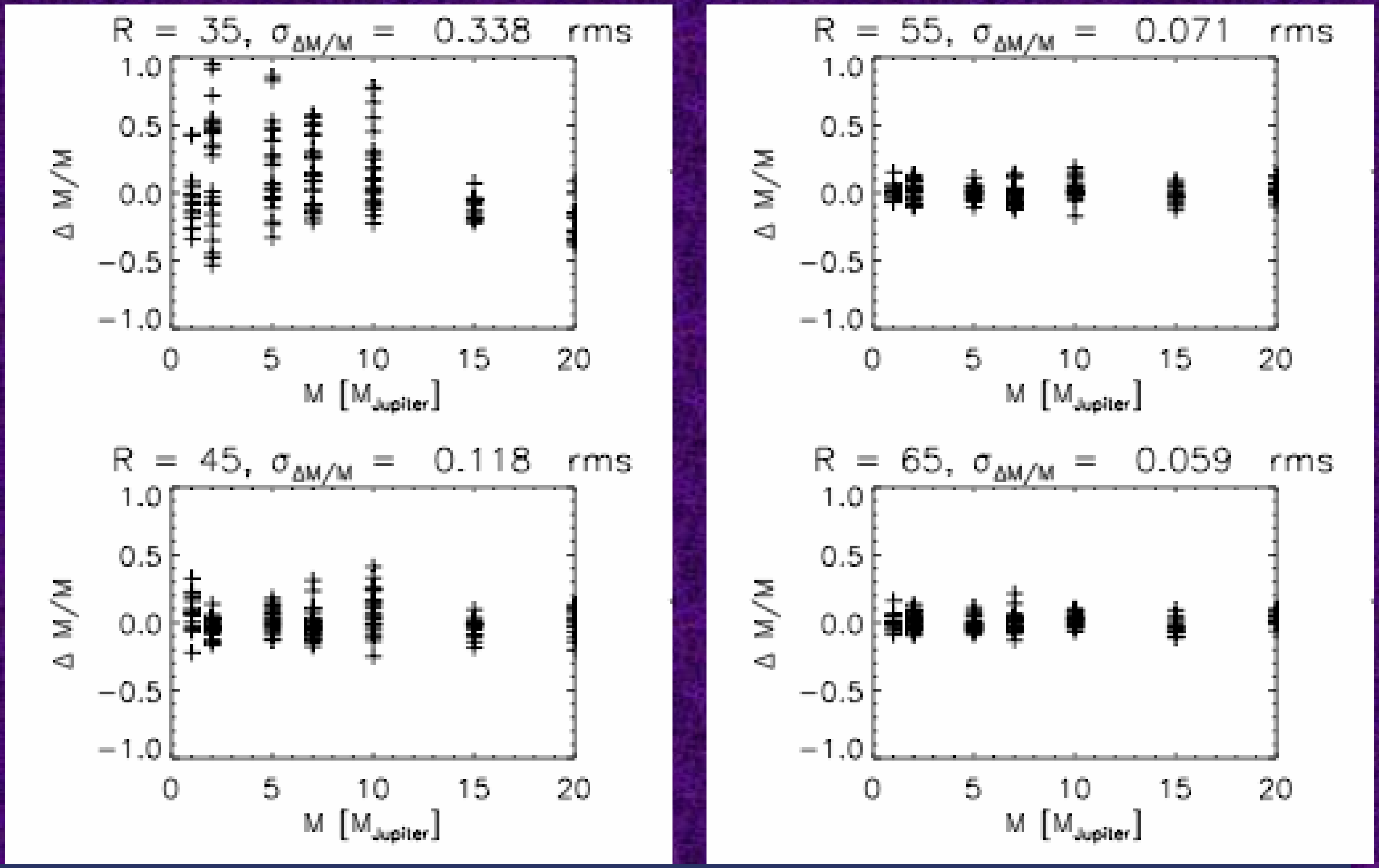
- Many historical arguments about “speckle lifetime” have driven varying analytic scaling-law predictions of ExAO sensitivity

Simulations rather than scaling laws



- High-resolution Monte Carlo translating-atmosphere simulations with realistic atmosphere profiles render these arguments moot
- Quasi-static effects still must be added in separately

Spectral characterization at SNR=20



- R=45 spectroscopy can measure gravity/masses to 10%
- Highly model and composition-dependent
- Given age and luminosity information, this becomes a model and composition constraint